STUDIES FOR STUDENTS

RELATIONS BETWEEN CLIMATE AND TERRESTRIAL DEPOSITS—*Continued*

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PART II. RELATION OF SEDIMENTS TO REGIONS OF DEPOSITION

INTRODUCTION

Upon a comparison of the character of the deposits laid down upon the topographically somewhat similar surfaces of large deltas but

under the most unlike conditions of temperature and rainfall, such, for instance, as the deposits upon the deltas of the Indus, the Amazon, and the Yukon, it is perceived that the climatic conditions existing over the surface of deposition form a factor of primary importance in governing the nature of fluvial and pluvial deposits. A proper interpretation of ancient continental sediments cannot be made, therefore, if the climatic factor be neglected, and on the other hand the deposits of ancient delta surfaces should contain a more or less accurate record of the climatic conditions of origin. But a closer inspection of modern deltas shows that different parts of the same delta surface exhibit markedly different conditions of deposition owing to the somewhat varying local geographic features, such as lakes, swamps, and natural levees, which may exist. In desert regions, as exemplified by the delta of the Helmund, the great internal river of Persia, portions not now used by the river are barren sandy deserts subjected to deep wind scour, occasionally in this instance exposing ancient ruins, and the corresponding heaping-up of aeolian deposits, while at the same time such shifting, shallow, and variable lakes as that of Seistan, the reservoir into which the Helmund drains, are giving rise to interstratified, truly lacustrine deposits.[1]

Therefore in the climatic interpretation of ancient continental deposits proper allowance must first be made for the geographic variations which occur within the region of deposition. The field studies must be sufficiently broad to lead to some recognition of the ancient geography before the ancient climate may be determined. To that end the modifications in deposit due to the influence of the local geographic conditions will first be discussed.

Influence of Nature of Surface of Deposition

PIEDMONT SLOPES—AERIAL DELTAS

These are more usually formed in arid or sub-arid climates, since in such the river waters progressively escape, after leaving the mountains, into the thirsty soil and air. The overloaded stream consequently throws down its burden of waste upon a slope which may vary from 100 feet per mile in the case of the coarser and steeper fans

[1] Col. Sir Henry McMahon, "Recent Survey and Exploration in Seistan," *The Geographical Journal of London*, Vol. XXVIII, 1906, pp. 209–228.

to those which may be as low in grade as five or ten feet per mile. The latter are built by the more slowly diminishing volume of the larger streams, and their sands or silts, when properly irrigated, form soils of the greatest richness. As an instance of the physical conditions which may exist upon such subaerial delta fans there may be quoted the following description by Davis of the plains of the rivers which flow north from the mountains of northern Afghanistan into the Kara Kum desert:

> The surface was absolutely plain to the eye, except for the dunes, and the dunes departed from the plain only as wind waves at sea depart from a calm surface. Although apparently level the plain has slope enough to give the Tejen, the Murg-ab, and the Amu rapid currents, in which these rivers carry forward a great volume of mountain waste. We were fortunate enough to see the Tejen and the Murg-ab in flood. The former had overflowed its channel and spread in a thin sheet for miles over the plain. The latter would have spread but for the restraint of dykes at Merv. Some of its waters had escaped farther upstream and came to the railroad, wandering across the plain among the dunes, a curious combination of too much and too little water supply.[1]

Following the inundation under natural conditions a temporary vegetation springs up, finally withering and giving place to the desert until the period of the next season of flood. Such districts of sedimentation give a maximum contrast of seasons of desert aridity alternating with periodic inundations; a contrast which is to be regarded as due not only to the arid climate but equally to the slope of the surface supplemented by the porous nature of the deposits, allowing of rapid drainage followed by a drying of the soil. In climates of a semi-arid character, as over the High Plains of the United States, the flood plains show a similarly well-drained character, the swampy areas being found more commonly among the dunes of the upland than over the river plain and due to aeolian more than to fluviatile action.[2] In wet climates the opportunity for deposition of waste upon such slopes is more rare and can occur in marked development only where streams in a highly loaded condition escape from lofty mountains. Such fans may be noted among the Alps with surfaces free from swampy areas, except, as in the case of the valley of the Upper Rhone, where

[1] W. M. Davis, *Explorations in Turkestan*, 1905, p 54, "Carnegie Institution Publications," No. 26.[1]

[2] See the Brown's Creek and Camp Clarke, Nebraska, quadrangles, "Topographic Sheets," *U. S. Geological Survey*.

opposing fans dam up the line of confluent drainage. The final conclusion, therefore, is that over such piedmont slopes there is a great freedom from areas of swamp and the greatest opportunity for drying and aeration of the soil between the times of flood. Such deposits should normally show complete oxidation of the iron and a complete absence of carbon. In hot climates evaporation from the soil is very rapid and oxidation of the humus is also rapid, resulting in the red clays characteristic of the moist tropical climates. Even the short intervals between rains which occur in the most pluvial of tropical regions are sufficient, therefore, to bring about the oxidation of the iron and elimination of the carbon from all but permanently swampy areas, giving rise to the red muds of the Amazon and Congo rivers.

In cool climates, on the contrary, evaporation and oxidation are both diminished in intensity with the result that carbon may accumulate upon slopes to an extent impossible in warmer climates, giving rise upon consolidation to carbonaceous sandstones or even conglomerates. The existence of the latter chemical conditions, leading to the accumulation of carbon even upon sloping surfaces, is found only in climates which approach a continuously rainy character and possess in addition cool summers. As an example, such climatic conditions are found at present upon the western slopes of Ireland, though the accumulating piedmont slopes are there wanting. Peat swamps, however, are observed to exist upon hilltops, slopes, and valley bottoms, covering one-seventh of the entire island. Many bogs possess a grade sufficient so that in times of excessive rain they may swell and burst and disastrously flood the lower valleys. Less familiar but still better examples are offered by the cool and humid maritime mountain slopes of Alaska. Of these Russell states:

About the shores of Unalaska and for fully 2,000 feet up its rugged mountain slopes the vegetation is essentially the same as at St. Michaels upon the Yukon delta. In climbing the steep slopes about Iliuliuk I often had great assistance from the dense mat of vegetation two or three feet thick, which, clinging to the rocks, converts their angular crags and shattered crests into smooth domes of soft, yielding moss. On the steep slopes, as in the swamps, the vegetation is always water soaked, owing to the extreme humidity of the climate in which it thrives. Lakelets are common on slopes and hillsides that would be well drained were it not for the spongy nature of their mossy banks.[1]

[1] "Notes on the Surface Geology of Alaska," *Bulletin of the Geological Society of America*, Vol. I, 1890, pp. 125, 126.

Turning to the past for illustrations of these conclusions, we may point out that the coarse, coal-measure conglomerates of the Narragansett Basin and the less coarse, but still conspicuous, Triassic conglomerates of the Connecticut Valley, both give evidence of rather local derivation and of continental deposition, evidence which cannot, however, as previously stated, be here discussed in detail. The local origin and coarse texture indicate deposition upon slopes of at least from five to ten feet per mile and possibly much greater, sufficient, under the usual climatic conditions, for good drainage. The Triassic conglomerates of the Connecticut Valley show a large amount of fragmentary fresh feldspar, iron completely oxidized, and no trace of carbon, either in the matrix or associated red shales, the fish fossils being found in the rare black shale bands. The conglomerates of the Narragansett Basin, on the other hand, with the exception of the Wamsutta beds, show a bleached matrix containing more or less carbon and are associated with a great volume of highly carbonaceous shales.

From these facts alone, therefore, it would be judged that the Carboniferous conglomerates, granting their subaerial origin, were accumulated during a period of cool and more or less continuously rainy climate.

The Triassic conglomerates, on the other hand, are associated with many features of climatic significance which also cannot be taken up here in detail, but which independently indicate a semiarid climate with hot summers and possibly cold winters. The characteristics, therefore, of these conglomerates, originating from the same geologic province, but in climatically dissimilar geologic times, are such as to emphasize the importance of the present conclusions regarding climatic influences upon the deposits of piedmont slopes. Further discussion of this subject must be left for the section on climatic influences.

LOWER FLOOD PLAINS—AQUEOUS DELTAS

The slope of graded streams progressively diminishes from source to mouth, the larger and longer the stream the flatter the grade tending to become. The deltas of the larger rivers commonly possess a slope of less than a foot per mile, and on the seaward margin pass into practically level salt-water marshes, underlaid by heavy deposits of

flocculated clay, giving rise to conditions unfavorable for either underground or surface drainage. In the case of piedmont slopes it was seen that in desert climates the greatest seasonal contrasts exist between too much and too little water, but that all parts fare much alike and become dried out through the greater portion of the year. Over the lower flood plains, on the contrary, such striking contrasts of swamp and desert are permanent features through series of years. Using the delta of the Colorado River as an example of one developed under highly arid conditions, Macdougal describes in a recent work how:

> At places where the river is cutting into gravelly and sandy bluffs, within the compass of one hundred feet may be found the most vivid contrasts of rank swamp vegetation and water-loving plants having broad leaves and delicate tissues with the toughened spinose, and hairy xerophytic forms of the desert.
>
> The quantity of food furnished by the swampy jungles is sufficient to support a vast amount of native animal life, and furnishes inviting feeding-grounds for migrating birds. The countless millions of young willow and poplar shoots supply food for the beaver, which bids well to hold out long in the impassable bayous and swamps against its trapper foe.
>
> Nearer the gulf are found great sloughs, in which are extensive fields of the "wild rice," while the land subject to the action of the overflow of the tides supports a carpet of salt-grass.[1]

Similar areas of more or less permanent swamp, increasing toward the seaward margin, may be noted as characteristic of other large deltas, such as those of the Nile and the Indus, developed as with the Colorado in truly desert regions. In ancient river deposits, therefore, an appreciable proportion of paludal deposits must be expected to occur over the terminal portions of the delta under all climatic conditions, and such must be allowed for in making inferences in regard to the ancient climate. As means for separating these geographic and climatic factors, however, may be noted the close association over the desert delta of paludal and desert conditions and the much smaller proportion of swamp which is permanent than in the case of more pluvial climates. In the long seasons of dessication all but the lowest bottoms become dried out and mud-cracked.[2]

[1] "The Delta of the Rio Colorado," *Bulletin of the American Geographical Society*, January, 1906, pp. 4, 10, 11.

[2] D. T. Macdougal, *op. cit.;* see Fig. 1.

A number of conditions besides the climate will be found, however, to affect the ratio over the marginal portion of the delta, of swamp to the well drained areas. These may be enumerated as follows:

First, a slowly rising water level tends to flood the lower portion of a delta and bring large tracts into the condition of permanent swamps. As such movements of water level are variable and intermittent the extent and ratio of the seaward paludal deposits seen in cross-section in ancient deltas will vary through the section. Such, however, will be practically absent from the region of the apex of the delta, but will be marginal to, and most commonly underlie, marine strata marking invasions of the sea.

Second, the contest of two or more rivers in building up a common flood plain or delta results in the damming back of the weaker members of the system. The paludal regions tend to migrate away from the greater sources of sediment.

Third, the possession of a wide flood plain, as in the case of the lower Mississippi Valley, is liable to result in a considerable area of back swamp, there being less infilling from the sides, and the river with its natural levees occupying a lesser portion of the whole.

As factors tending on the contrary toward good drainage of the lower river plains may be mentioned: first, a stationary or even slowly subsiding water level; second, the possession of a flood plain by a single river such as the Nile as contrasted with the Euphrates-Tigris system of Mesopotamia; third, aggradation within a confined valley, exemplified by the Great Valley of California, where side wash is present to such an extent that the ground slopes gently but continuously from the hillsides to the trough of the valley.

ELIMINATION OF LOCAL GEOGRAPHIC FACTORS

The preceding discussion has dealt with the upper or lower flood plains of the river system as a whole and it has been seen that the character of the sediments deposited must be largely influenced by the physical conditions existing in the region of deposition, whether near the mountains as piedmont slopes, or at a distance as deltas built into shallow seas. Within the confines of the terminal deltas, however, there exists greater local diversity of conditions.

In the study of ancient deposits now exposed to view in scattered

and fragmentary sections such a comprehensive knowledge of the limits and surface nature of the original formation becomes, however, a difficult problem. Certain rules should, therefore, be formulated, by following which the local geographic conditions may be most largely eliminated from the problem of the climatic interpretation. Such rules may be stated as follows: First, the general direction of the former land on the one hand and of the sea on the other is ordinarily readily determinable. The deposit is coarsest, the slope of the river-plain steepest, the surface and underground drainage best, over those portions of the deposit nearest the source of sediment. The highest proportion of continental as opposed to marine strata will ordinarily be found in the same region. This, therefore, will be the most favorable place for the study of all but the chemical or organic deposits. Second, toward the landward or upstream side the thicknesses of the formation will commonly vary along successive outcrops. Such variable thicknesses may be due either to excessive subsidence causing drainage of the sediments *toward* and into the basin, filling it in; or excessive sedimentation building up piedmont slopes, the excess passing *outward* in other directions, or to a combination of both conditions. Observation of ancient geosynclines, such as that which faced Paleozoic Appalachia, shows that in many cases excessive sedimentation in the vicinity of some large river appears to be the more common and fundamental cause, the zone of maximum deposition being characterized at the same time by the coarsest material and a decreased proportion of chemical and organic deposits. In continental formations, therefore, the region of maximum thickness, as well as greatest coarseness, is usually the most favorable for the study of the mechanical conditions of deposition. Third, the regions of scanty sedimentation and the paludal zone facing the ancient water body are the most favorable for the development of chemical and organic deposits. Under arid climates will here be found beds of salt and gypsum intercalated with both continental and marine argillaceous strata, possibly associated with a small amount of variegated shales; but, judging from geological experience, never deposits of carbon. Under typically rainy climates, on the other hand, whatever occasional deposits of salt and gypsum may form are speedily washed away during a following season of rain, and the permanently

flooded condition of the swamp areas leads to the preservation of carbonaceous strata.

With the accentuation of climates toward aridity or toward a cool and continuously pluvial condition, these chemical and organic deposits, developed most typically on the distal margin of the delta, spread inland and become of greater geological importance, as illustrated by the brine pools of the desert delta of the Volga, on the one hand, or the impenetrable flooded jungles of the Amazonian silvas, on the other.

Climatic Influences in Regions of Deposition

The geographic and climatic influences in the regions of erosion produce two effects in the region of deposition. One, a chemical and mineralogical influence which becomes generalized and vague with prolonged transportation; the other through variations in erosion causing variations in the coarseness and quantity of waste, also becoming masked by the effects of long transportation. On piedmont slopes, therefore, being nearer the headwaters, the climatic conditions of erosion, of transportation, and of deposition all find obvious expression; but over the more distant parts of a river system the more conspicuous factors governing the nature of the sedimentation are the *variable nature of the transportation*, regulating the coarseness and quantity of the waste, and the *variable climatic conditions existing in the region of deposition*, largely governing the chemical and mineral nature of the deposit. The microscope and the chemical analysis will still, however, be able to trace underlying influences due to the nature of erosion, as indicated by existing deposits of loess in Mississippi and red laterite muds spread in places upon the bottoms of tropical seas.

In taking up in detail the present topic of the influence of climate in regions of deposition, the effects upon the deposits of four kinds of climates may be considered, namely, constantly rainy, intermittently rainy, subarid, and arid. The effects of increased cold, by preventing evaporation, produce results similar to an increased and more continuous rainfall. Cool summers rather than cold winters are more effective in this way and lead in northwestern Europe to the production of extensive peat deposits in regions which receive but twenty-five to

forty inches of rain per year, distributed, however, rather uniformly through the seasons. Where the cold is prolonged and intense, however, as found over the tundras within the Arctic Circle, a fifth class, that of the frigid climates, may be considered.

EFFECTS OF CONSTANTLY RAINY CLIMATES

Constantly rainy climates are defined by W. Köppen as those where no month has less than fifteen rainy days.[1] Such climates are dominant south of south lat. 45°, touching southwestern Patagonia, Tierra del Fuego, and southern New Zealand. Another large area exists in the North Atlantic, touching Iceland and approaching the shores of Ireland, Scotland, and Norway. Certain tropical areas also have nearly constantly rainy climates, at least six days in every month being rainy, the northern half of the basin of the Amazon being the most notable from the present point of view. In such regions the forest vegetation attains its maximum development, the cooler parts of the temperate zones hardly lagging behind the most favored tropics in luxuriance, provided that the winter winds are moist, the soil and antecedent vegetation have been spared by glaciation, and the more recent forests by man. On the southwestern side of Patagonia, for instance, in south lat. 55°, Hatcher speaks of a vegetation so profuse as to suggest that he had been transported into the midst of some tropical jungle.[2] Dusén states also that in the interior of Tierra del Fuego, near the harbor of Puerto Angosta, the typical virgin forest reminded him of the West African virgin forests which he had seen.[3]

In this connection the observations of Darwin upon the forests of Tierra del Fuego are significant. He mentions the thick bed of swampy peat covering the steep slopes above the timber line while of the almost impenetrable forest below he states:

In the valleys it was scarcely possible to crawl along, they were so completely barricaded by great mouldering trunks, which had fallen down in every direction. When passing over these natural bridges, one's course was often arrested by sinking knee-deep into the rotten wood; at other times when attempting to lean against a firm tree, one was startled by finding a mass of decayed matter ready

1 *Bartholomew's Physical Atlas*, Vol. III, 1899, Plate XIX.

2 *Princeton Patagonia Expeditions*, Vol. I, 1903, p. 150.

3 P. Dusén, "Ueber die Vegetation der feuerländischen Inselgruppe," *Englers Jahrbücher*, Band XXIV, 1898.

to fall at the slightest touch.[1] . . . . The entangled mass of the thriving and the fallen reminded me of the forests within the tropics—yet there was a difference: for in these still solitudes, death, instead of life, seemed the predominant spirit.[2]

These statements bring into prominence the slowness of organic decay in cool climates and its rapidity in warm, permitting the accumulation of dead vegetable matter in the one region, quickly removing it from view in the other. Schimper also calls attention to the relative poverty of humus in tropical soils and emphasizes the statement that peat is never produced in the tropics except on mountains over 1,200 meters in height.[3]

Influence of arctic climates.—Within the colder portions of the temperate zones a lesser rainfall and severer winters result in a somewhat diminished luxuriance of vegetation, but, as previously noted, on account of the less intense evaporation and oxidation notable deposits of carbon may still result. In the interior of Alaska the precipitation varies from about ten inches per year on the eastern boundary to about twenty-five inches per year where the interior province passes on the west into the relatively humid Behring Sea province. The heaviest precipitation is in summer, but is always moderate in amount.[4] Under these conditions of rainfall, which in a hotter climate would lead to aridity or semiaridity, there is here found on the lowlands, where these are within the timber line, a luxuriant forest of spruce and willow with an undergrowth of cryptogamic character.

Within the Arctic Circle beyond the limit of arboreal vegetation exist the vast treeless moss-covered plains known as the tundra, perpetually frozen below the depth of a foot or two. In the far north the tundra may be developed under a rainfall of not over ten inches per year, but in such regions the vegetation is meager and barely covers the soil. Farther south, however, and in more rainy districts a thick carpet of peaty vegetable matter may accumulate. A tundra of this character is found on the delta of the Yukon under a rainfall of from

[1] "Ascent of Mount Tarn," *The Voyage of the Beagle*, June, 1834.

[2] *Ibid.*, "Scenery of the Mountains and Retrospect."

[3] *Plant Geography*, 1898 (Eng. trans.), pp. 381, 382.

[4] Cleveland Abbe, Jr., "Climate of Alaska," pp. 147, 154–157, Professional Paper No. 45, *U. S. Geological Survey*, 1906.

eighteen inches at St. Michaels to thirty-three inches at Fort Alexander, the precipitation occurring largely as rain and from May to October.[1]

Russell, speaking of the tundra as developed upon the delta of the Yukon and the south, says:

General characters.—The tundra in typical localities is a swampy, moderately level country, covered with mosses, lichens, and a great number of small but exceedingly beautiful flowering plants, together with a few ferns. The soil beneath the luxuriant carpet of dense vegetation is a dark humus, and at a depth exceeding about a foot is always frozen. On its surface there are many lakelets and ponds surrounded by banks of moss even more luxuriant than on the general surface. It is not always a level plain, however, but is frequently undulating and may surround and completely cover hills of considerable elevation. The dense tundra vegetation also extends up the mountain side and occupies the entire region where the conditions are favorable for its formation. At the localities where I examined it the whole surface, excepting the faces of steep cliffs and the summits of high mountains, was covered with the same dense brown and green carpet. The characteristics are the abundance of mosses and lichens and the absence of trees. Cryptogamic plants make more than nine-tenths of its mass. On their power to grow above as they die and decay below depends the existence of the tundra.

The depth of the humus layer beneath the moss was found to be about two feet at St. Michaels. A mile east of the village it was about twelve feet. In the delta of the Yukon a depth of over fifteen feet was seen at one locality. As satisfactory sections are rare, these measurements do not indicate its average thickness. A depth of 150 to 300 feet has been assigned by several observers to the tundra where it is exposed in a sea cliff on Eschscholtz Bay, at the head of Kotzebue Sound.[2]

Chemical nature of deposits of constantly rainy climates.—The distinctive chemical effects are to be noted in the absence or small amount of the soluble elements, embracing iron, magnesia, lime, potash, and soda, and in contrast, the presence of carbon. Owing to the diminished evaporation and the constant saturation of the soil of the entire flood plain, aeration and oxidation of the soil is prevented while the decaying organic matter results in deoxidizing effects. Where the leaching and deoxidizing actions have fullest opportunities for work, as in the clay soils beneath swamps, all soluble plant food may be leached out. Where the chemical effects are less pronounced

[1] Cleveland Abbe, Jr., *op. cit.*, pp. 146, 152.

[2] I. C. Russell, "Notes on the Surface Geology of Alaska," *Bulletin of the Geological Society of America*, Vol. I, pp. 125–27.

the iron may be deoxidized and concentrated, but not eliminated. The colors of the deposits are consequently white or black or gray. These opposed relations of carbon and iron and the leaching of soluble components from the fire-clays underlying swamp deposits as derived from the study of modern instances are seen to correspond to the nature of the coal-measures and the conditions of moisture necessary for their formation have long been emphasized, but the added condition of coolness as favoring more extensive accumulations of carbonaceous character has not until within the past few years been generally recognized. The great influence of coolness was perhaps first pointed out by Russell, who in connection with the carbonaceous deposits of Alaska expresses the following opinion:

A possible origin of coal seams.—So vast is the amount of vegetable matter now imprisoned in the tundra of the North, that I venture to suggest that possibly some coal seams may have had a similar origin.

This suggestion does not seem so very unreasonable when one remembers that except in the circumpolar tundra, deposits of vegetable matter are nowhere accumulating at the present day to anything like the extent or thickness required for the formation of coal fields like the one, for example, of which Pennsylvania still retains a remnant. Botanists will say at once, in opposition to this suggestion, that the flora of most of our coal fields, and especially those of Paleozoic age, indicate tropical or sub-tropical conditions. The flora of the tundra, however, like the plants of the Carboniferous, is essentially and characteristically cryptogamic. Two species of Equisetum, which may be considered as representing the Calamites of former times, flourish with rank luxuriance over great areas along the Yukon.[1]

It is further desired at this place to call attention to the other chemical characters of the deposits, by which even without the presence of carbon the rainy nature of the climate may be inferred. Various investigators have shown that in those portions of tropical soils leached by heavy rainfall which are soluble in hydrochloric acid soda is quite absent, potash is low, the residual soils usually not possessing over 0.1 per cent.[2] of potash and the river alluvium not over 0.2 to 0.3 per cent.,[3] the leached alluvium of Assam, a region of extremely heavy rainfall, containing but about one-half the potash of the drier soils of the Indo-Gangetic plain. The same characteristics

[1] *Op. cit.*, pp. 127, 128.

[2] E. W. Hilgard, *Soils*, 1906, p. 355.

[3] *Op. cit.*, pp. 412, 413.

would be evident upon a complete analysis of the alluvium, but unfortunately for geological purposes such complete analyses of soils are seldom made. Lime exists in higher percentage in river alluvium than in upland soils, but Mann has shown that it is extremely deficient in the soils subjected to heavy rainfall, the general average in the Assam alluvium soluble in hydrochloric acid being about 0.08 per cent., as against nearly 1.0 per cent. in the average Indo-Gangetic soil.[1] It is noticeable that in the true tropical soils the content of magnesia is considerably above that of lime; a fact readily intelligible from the more ready solubility of lime in carbonated water.[2] That it is leached out also, however, is indicated by its content of 0.5 per cent. in the soluble portion of the Assam tea soils as contrasted with its presence to the extent of 1.3 per cent. in the soluble portion of the Indo-Gangetic alluvium.[3] The iron of the Assam soils is also low, but it is not deficient in tropical soils in general, giving on the contrary a characteristic red to such lands as Madagascar and Ceylon.

The continuously rainy climates may be divided into those situated in the equatorial belt, usually possessing at least short dry seasons, and those situated in the cooler parts of the temperate zones. The preceding discussion on the chemical distinctions has been largely based upon soils of the torrid zone or warm temperate, as in the case of the Assam alluvium. In the cold temperate regions recent glaciation has in many cases prevented the establishment of normal chemical relations between the rocks and the atmosphere, but such observations as have been made indicate, as was shown in Part I, that decomposition is greatly reduced. From the foregoing it may be concluded that the broad association of carbon with sediments which are thoroughly decomposed and leached throughout is the mark of continuously rainy climates which are tropic or at least warm temperate; with sediments imperfectly decomposed and incompletely leached the mark of more or less continuously rainy climates which are in addition cool or cold. The best microscopic test after the lithification of the alluvium may be the absence or presence of potash minerals. The carbonaceous shales of the anthracite coal-measures of Pennsylvania, except the fire clays immediately below the coal beds, possess a marked abundance of muscovite, indicating the presence of consider-

[1] Hilgard, *op. cit.*, p. 413. [2] *Op. cit.*, p. 405. [3] *Op. cit.*, p. 413.

able potash and magnesia. From this would be inferred an origin under cool climatic conditions, in line with the inference previously drawn from the Carboniferous conglomerates of Rhode Island—calling attention to the importance of microscopical or chemical examination and comparison of argillaceous sediments of similar continental but presumably of unlike climatic origin. In contrast with the muscovite shales of the coal-measures may be noted the absence of muscovite in the carbonaceous shales of the Hudson River and Hamilton periods which underlie the Carboniferous and have consequently been subjected to equal or even greater metamorphism. While these latter shales are of marine origin it is not clear that that fact alone could lead to this peculiar distinction.

That a cool climate, while undoubtedly favorable, is not necessary for the production of coal-measures is, however, shown at the present time by the swamps of the Amazon and, in the past, by the warm-temperate flora of the Eocene coals of the Pacific slope. The absence of frost rather than a hot climate is, however, all that is necessarily implied by the Eocene vegetation.

EFFECTS OF INTERMITTENTLY RAINY CLIMATES

Intermediate character of deposits.—Climates of this class are such as characterize those portions of the world where crops may be grown without the aid of irrigation, but where one or more months may be relatively free from rain. Under these familiar conditions the soil of the flood plains normally contains considerable humus, but much of it is yellow or red, instead of brown or black, from the subordination in quantity of the humus to the ferric hydrate. The greater part of the soil of flood plains is sufficiently dry during a growing season for such crops as corn and cotton. The clays are slightly calcareous and occasionally sufficiently so to give rise to the so-called "buckshot" soils such as are found over portions of the Mississippi flood plain.[1] The subsoils of such plains are observed to carry more compact clay and less humus than the soil, the carbon thus gradually disappearing with depth in aerated soils.

Only in the lower bottoms or abandoned ox bows is the land so saturated with moisture that swamp vegetation dominates, organic

[1] E. W. Hilgard, *Soils in the Humid and Arid Regions*, 1906, p. 116.

matter indefinitely accumulates, and the iron is eliminated or at least reduced partly to the ferrous conditions, giving rise to the blue and green clays found in the subsoils of certain undrained lands. From the discussion on the climatic significance of color, as given in a later portion, it is believed that the usual yellow or brown of such flood-plain deposits frequently deepens upon the consolidation into shades of red or deeper brown. When such flood-plain deposits are buried and lithified the upstream portions will consequently be found somewhat more arenaceous, varying from red to brown sandstones and usually inclosing red, green, and some black shales; the last in very subordinate quantity. Over the terminal land portions of the deposit on the contrary the sandstones should be finer grained and the quantity of shales should increase. With this increase in shales, grey, green, and black varieties should be relatively more abundant and thin lenticular discontinuous coal beds may be expected to occur. Thick, uniform, and widespreading coal deposits are, however, theoretically impossible, since the swamp areas are restricted to the lowest-lying portions of the plain.

Organic characteristics.—A forest growth normally covers the entire surface of such flood plains, varying from mesophytic to hydrophytic types, salt marshes marginal to the sea and internal shallow lakes alone being occupied by reedy growths. The alternate wetting and drying occurring in such soils leads to the rapid humification of animal and vegetable substances, and ultimately to their complete destroyal. Consequently, but few fossil evidences will remain beyond the casts of leaves and trunks occurring in the lighter-colored shales and sandstones, and the preservation of some carbonized tissues in the occasional black and coaly shales.

Conclusion on unappreciated extent of such deposits.—In conclusion it may be said that the deposits of intermittently rainy climates are of a chemical and organic character intermediate between those of continually rainy climates on the one hand and those of a subarid or arid character on the other, lacking the sharply distinguishing characteristics of each. In consequence of the absence of such distinctive marks such deposits, while abundant, may be the most difficult of continental formations to distinguish and convincingly separate from those of shallow-water, off-shore marine origin.

The section of the Ganges delta given by the Calcutta borehole shows no trace of marine deposits, but on the other hand the proofs of land surfaces in the form of ancient swamp deposits, even in this marginal portion of the delta, were encountered only at two levels in the 481 feet of the boring.[1] Scattered vegetable matter and the bones of terrestrial mammals and fluviatile reptiles which were found, while suggestive of continental deposition, may possibly occur in off-shore marine deposits and alone do not conclusively demonstrate the continental origin. Farther inland, at Umballa, on the watershed of the Indo-Gangetic plain, a bore-hole 701 feet deep passed through alternations of sand and clay, the colors usually red or brown but with some clays blue and black. In places the bore-hole encountered a few pebbles and bowlders, but no mention is made of organic remains, which according to Medlicott and Blanford occur but rarely in the alluvial formations of the Gangetic plain.[2] Numerous layers of Kankar (concretionary strata of calcium carbonate) suggest the previous existence at this place of the semiaridity which now prevails in that region. The Mississippi delta shows much of the same characteristics as that of the Ganges at Calcutta. Consequently, where sands and clays or their consolidated representatives constitute a formation with no trace of marine fossils but possessing even fragmentary remains of land life, it is to be concluded with high probability, if no other evidence overweighs the decision, that the entire formation is continental and, further, if no positive marks of other climatic conditions are evident, that it was probably formed on a river flood plain under the intermittently rainy climates, which, though at times diminished and again magnified in importance, have yet existed uninterruptedly through all geologic time and formed those shifting zones within which the chemical activities of the atmosphere and the biologic forces of terrestrial evolution have found their fields for fullest action.

EFFECTS OF SEMIARID CLIMATES

Chemical and structural characteristics.—Semiarid climates are those where irrigation is usually necessary for the maturing of crops

[1] Medlicott and Blanford, *A Manual of the Geology of India*, Part I, 1879, pp. 397–400.

[2] *Op. cit.*, pp. 401, 402.

or where protracted periods of drought are to be expected during certain seasons of the year. In temperate latitudes this corresponds roughly to between ten and twenty inches of annual rainfall. Under such conditions, as illustrated over the High Plains of the United States and much of the Cordilleran province, the humus is oxidized out of the soil more rapidly than in more rainy climates, being deficient in amount but rich in nitrogen; the iron is not leached or concentrated, except in the presence of occasional shallow lakes or swamps; the soil is uniformly high in potash, lime, and magnesia. The potash is, moreover, largely in the form of comminuted orthoclase, giving less plasticity to the finer elements of the soil.[1] Very little distinction is to be noted between the soil and subsoil of alluvial plains.

The swampy portions of the flood plain largely become dry during the long dry season, excluding fishes and offering favorable breeding-places for mosquitoes during the times that the swamps exist. The delta regions of subarid climates are consequently particularly malarious. As examples of such deltas may be cited those along the north shores of the Mediterranean. The Gedis, flowing into the Gulf of Smyrna, possesses extensive delta swamps dry during the summer,[2] while the small proportion of swamp in the case of the Nile delta in a truly arid climate is to be compared with the extensive swamps of the Mississippi. Other factors besides climate, however, may assist in governing the ratio of swamps in the latter cases. The thorough seasonal oxidation which is thus allowed of nearly all deposits except those made in permanent water bodies should result, upon their incorporation into the geological record, in a marked dominance of deep-red and brown shales and sandstones, a moderate amount of variegated shales, confined almost entirely to the marginal portion of the deposit, and few or none holding carbon. Lime will exist disseminated in noticeable amount through both shales and sandstones and may occasionally give rise to markedly nodular or solid calcareous strata.[3] The microscope should show some muscovite and in addition a noticeable amount of feldspar in the finer portions

[1] E. W. Hilgard, *Soils*, 1906, chaps. xx, xxi.

[2] G. R. Credner, "Die Deltas, ihre Morphologie, geographische Verbreitung und Entstehungsbedingungen, *Petermann's Mitth. Ergänzungsheft*, No. 56, Vol. XII, 1878, Plate I.

[3] Medlicott and Blanford, *Geology of India*, 1879, Part I, chaps. xvi, xvii.

of the rock. The contrast between the river deposits of humid and subarid regions is well brought out by the comparison of the alluvium of the Indo-Gangetic plain with that of the Brahmapootra in Assam, the material in both cases coming from the same mountain system.[1]

The most marked chemical distinction of subarid flood-plain deposits from those of truly arid regions is found in the small quantity of evaporation deposits of calcium carbonate, gypsum, and salt, but especially of the two latter. Lime may be quite abundant, as shown by the Kankar of the Indo-Gangetic plain, its importance depending largely upon the quantity in solution in the river water. Gypsum and salt, however, formed by the evaporation of salt lagoons bordering the sea, are largely washed out by the rains and floods of the rainy season. As gypsum and salt impregnations of clay strata they may be preserved and sometimes as purer deposits of salt, as illustrated by the deposits now occasionally formed on the Rhone delta, as noted long since by Lyell,[2] in a climate which approaches subaridity. Such deposits cannot be formed, however, in anything like the areal extent or thickness with which they may occur in truly arid regions. Gypsum in delta deposits is less an indication of aridity than salt, since the former is precipitated upon the evaporation of 37 per cent. of normal sea water while the precipitation of salt only begins when 93 per cent. has been evaporated. It is to be noted, however, that the majority of recent sediments containing gypsum are found in arid climates, and where occurring as impregnations in ancient deposits which were not laid down in contact with sea water would seem surely to indicate a high degree of subaridity bordering upon truly arid conditions.

The alluvial soils of semiarid flood plains are particularly liable to become deeply mud-cracked during the seasons of drought, but this cracking may or may not be preserved in the sedimentary record.[3] Over the regions of alternating sands and clays where the clay is not calcareous the conditions are most favorable for the formation and preserval of mud cracks. The importance of mud-cracking in further drying out the soil and tearing the roots of plants has recently been

[1] E. W. Hilgard, *Soils*, 1906, pp. 410–14.

[2] Charles Lyell, *Principles of Geology*, 9th ed., 1853, p. 259.

[3] J. Barrell, *Journal of Geology*, Vol. XIV, pp. 528–33.

pointed out by Hilgard.[1] The climatic point where mud-cracking becomes broadly effective upon the clays of a flood plain is therefore rather a critical one tending to separate the floral characteristics of well-watered from subarid climates.

Floral characteristics of semiarid flood plains.—One of the most secure means at present commonly used to determine the climate of a past age consists in the study of a fossil fauna and flora, the identification of genera and species, and the inference that the optimum climatic environment for such organisms has remained the same from the past to the present time. As examples may be cited the conclusions in regard to the warm polar climate of the Miocene based on the presence of magnolias in Greenland and the same in Mississippian times as determined by fossil corals in the rocks of Spitzbergen. Such strictly paleontological sides of the problem are beyond the province of the present article, but there may be profitably considered the relations between climate and the kind of fossils to be expected and certain general adaptive characteristics of plants or animals to arid or moist, cold or warm conditions, especially when these are of a nature which may be preserved. The present statements will be chiefly confined, however, to the effects of semiarid climates upon vegetation.

The vegetation of the flood plains of semiarid climates is more largely arboreal than that of the inter-stream slopes.[2] Many large tracts of the flood plain away from the river banks are, however, either sparsely covered with trees or given over to grass land. Even the latter may find difficulty in existing where an unfavorable nature of alluvial deposit is added to the unfavorable conditions of a hot or dry growing season.[3] The occupancy of the soil by grass or forest depends upon the underground water. For forests there must be an adequate amount of moisture in the subsoil during the growing season, though this water may have come from winter floods or rains. For grassy plains the water in the subsoil is immaterial, the essential con-

[1] *Soils*, 1906, p. 112.

[2] A. F. W. Schimper, *Plant Geography* (Eng. trans.), 1898, Map 3.

[3] Views of piedmont and terminal flood plains of the semiarid belts of the United States may be found in various reports. For a study, with photographs, of the vegetation of the Rhone delta of the Mediterranean in a climate which approaches semiaridity see *Flahault et Combres*, Sur la flore de la Camargue et des alluvions du Rhone, *Bulletin de la société botanique de France*, T. 41, 1894, pp. 37–58.

dition being a moist soil during the season of growth.[1] Although the level of the ground water in flood plains of even subarid climates may lie not many feet below the surface, the alternate stratification of fine sand and clay which is frequently present is very unfavorable for a forest vegetation. The clay is capable of carrying the water upward to a greater height, even as high as ten feet, but transmits it very slowly. The sand, on the other hand, cannot lift the capillary water more than one or two feet, but does this very quickly.[2] If the upper portion of a sand stratum is dry, the plants cannot feel the moisture below and will fail to send roots after it. In the presence of such strata a vegetative covering of bunch grass is to be expected, leaving no appreciable organic record. A deep loamy soil favorable for storing water and for its capillary rise is the most favorable condition for the growth of trees and shrubs over semiarid flood plains. The roots in such cases strike downward rather than horizontally and may penetrate to great depths, twenty feet being not uncommon.[3] The angle of penetration of fossil roots is therefore a matter of importance from a climatic point of view. The strong oxidation acting at the surface normally destroys all vegetable tissues before they become buried in the course of time below the deep zone of oxidation, but there is a chance of finding casts of downward-branching rootlets in massive arenaceous shales and more rarely of vegetable remains buried by superficial accumulations. It is seen, therefore, that in the river deposits of semiarid climates casts of logs are most likely to be preserved in the sands deposited in the neighborhood of stream channels. At a distance from the channels, wetting and oxidation would tend to destroy the logs and larger fragments if such existed, before sufficient time had elapsed for burial. Root impressions of trees in such regions would be of more common occurrence than trunks and confined possibly to what were originally deep loamy sands. The herbaceous types of vegetation, however, are the more common over the well-drained portions of truly semiarid flood plains, and the plant impressions recorded in the strata would consequently be of small size compared to those of the large and luxuriant vegetable forms of more rainy climates.

[1] *Op. cit.*, pp. 164–75.

[2] E. W. Hilgard, *Soils*, 1906, pp. 202–13.

[3] *Loc. cit.*, pp. 167–83.

The above discussion is based on the present floral societies, composed almost wholly of flowering plants. The conclusions, however, in regard to the climatic relations of herbaceous and arboreal vegetation may with probability be extended backward in time to ages as early as the Devonian, when all plants were either cryptogamic or gymnospermous, since in the later Paleozoic, long before the advent of the Mesozoic phanerogams, plant societies existed then as now which included forms from arboreal to herbaceous and ranged in adaptation from hygrophilous to xerophylous. The present usual restriction of cryptogamic vegetation to small forms occupying habitats moist, shady, or cold, habitats not strongly sought by the higher vegetation, did not then necessarily hold; conditions to some extent perpetuated in Australia, where tree ferns still abound in the coastal districts of New South Wales and Victoria, and vascular cryptogams with xerophytic adaptations are known to occur in other portions of the island continent.

In illustration of these conclusions a comparison may be made of the fossil vegetation of the Mauch Chunk (Mississippian) shale of eastern Pennsylvania, believed by the writer from other considerations to be a continental deposit of a semiarid climate,[1] with the flora of the overlying coal-measures, believed to be continental deposits of a climate cool and rainy. In the Mauch Chunk strata, as observed by the writer, impressions of small plant fragments are not uncommon, consisting of first, the fragments of slender grasslike reeds probably belonging to the equisetae; second, impressions of flattened, straplike coarser stems and leaves up to an inch in width and exhibiting suggestions of parallel venation; third, impressions of stems with close-set spiny leafage, the spines not being over half an inch in length; fourth, casts of roots showing branching rootlets, the latter clothed with fine tendrils. The roots occur in massive argillaceous sandstones and in favorable cases are exposed by the rock fractures for depths of a foot with indications of being considerably more extensive. A striking feature of those root casts found in place is that they branch downward and not horizontally. Other observers have detected a leathery character in certain of these plant impressions. No casts of logs have

[1] J. Barrell, "Origin and Significance of the Mauch Chunk Shale," *Bulletin of the Geological Society of America*, Vol. XVIII (1907), pp: 449–76.

been seen by the writer or described by others and no carbon from the plant tissues is ever preserved. These characteristics are opposed throughout to those of the overlying carbonaceous beds of the true Carboniferous. In these the carbon is preserved, impressions of logs are abundant, the vegetation is coarse and luxuriant, and grasslike forms give place to a water-loving forest growth. The roots preserved in the underclay show no such tendency to penetrate constantly downward and in the case of the stigmaria are developed into stolen-like forms such as are possessed by many existing marsh plants.

The conclusions as to climate, based on the character of the vegetation in the case of these late Paleozoic formations and determined from adaptive relations observed to exist at present in quite different divisions of the vegetable kingdom, are thus seen to be in harmony with conclusions based on a number of other and independent lines of evidence. The latter, however, cannot be given at this place.

The animal life also shows adaptations to the climate, but these are far from being as strongly marked or so dominated by climate as in the case of plants, so that neither can a discussion of such general characteristics be considered under the present subject.

EFFECTS OF ARID CLIMATES UPON FLUVIAL AND PLUVIAL DEPOSITS

Chemical characteristics, evaporation deposits.—Arid climates, those of true deserts, typically possess no drainage to the sea and no agriculture is possible without either natural or artificial irrigation. Fluvial and pluvial deposits may, however, be abundantly developed, owing to the torrential nature of the occasional rains acting upon a loose and unprotected mantle rock. In this hasty transfer of disintegrated rather than decayed rock débris but little leaching is likely to occur, soluble and insoluble materials remaining together, the two tending to become somewhat separated by later and local action. The rainfall of such regions is, in the temperate zone, less than ten inches per year.

As noteworthy examples of deltas in arid climates may be cited those of the Volga, the Indus, the Nile, and the Colorado. The lime in such may form still more striking inorganic deposits than the "Kankar" of the subarid flood plains of India, forming such incrustations

as the massive travertine and caliche deposits of Arizona and Mexico.[1] In other cases, however, the content of lime may be no higher than in the deposits of subarid flood plains, the percentage of dissolved lime in the river water to undissolved detritus apparently having a strong influence in this respect. For example, the deltas of both the Rhine and the Rhone, especially the latter, show a considerable proportion of calcium carbonate due to the highly calcareous nature of the formations subjected to erosion, supplemented in the case of the Rhone by the approach toward a semiarid climate over its delta in the Mediterranean Sea. This delta consists in large part of sand cemented by lime.[2] In the deposits of the Nile delta, on the other hand, calcium carbonate is probably no more or possibly even less abundant than in the case of the Rhone. Analyses by Regnault of fresh Nile mud gave 22 per cent. of carbonates, of old Nile mud gave 11 per cent. Other analyses by Knop from other localities gave, however, only 4.1 to 4.7 per cent. of carbonates in the dried inorganic residues of Nile mud.[3] These may be compared with 0.1 per cent. of $CaCO_3$ as the average content in three alluvial soils of the Ohio Valley and 1.38 per cent. of $CaCO_3$ in two alluvial soils of the Mississippi Valley.[4] In the delta muds of arid climates the proportion of true clay may be low, and alkalis exist, largely either in the form of comminuted feldspar or as soluble alkaline salts in the surface soil. Brine pools and gypsum deposits will be not uncommon in the lower areas, especially near the margins of the deltas. Dense reedy jungles and fever-breeding salt swamps frequently dry at some season of the year may be common, but the presence of evaporation deposits with the decolorized shales is a characteristic which separates them from those of semiarid climates.

Those parts of the potash and soda which are dissolved from the silicate minerals and form alkali crusts or flat lands in arid regions are kept near the surface, being carried upward by capillary action in the dry season and washed downward a short distance by the occa-

[1] W. P. Blake, "The Caliche of Southern Arizona," Abstract, *Engineering and Mining Journal*, Vol. LXXII, 1901, pp. 601, 602.

[2] G. R. Credner, "Die Deltas, ihre Morphologie, geographische Verbreitung und Entstehungsbedingungen," *Petermann's Mitth. Ergänzungsheft*, No. 56, Vol. XII, 1878, p. 16.

[3] G. R. Credner, *op. cit.*, p. 15.

[4] G. P. Merrill, *Rocks, Rock-Weathering, and Soils*, 1906, p. 351.

sional rains or floods. The diagrams given by Hilgard show that in clay lands the bulk of the alkali is within two feet of the surface and in sandy lands within seven feet.[1] Medlicott and Blanford state that in the worst alkali tracts of India sweet water is obtainable at depths below sixty to eighty feet.[2] Except in the most arid regions the soluble alkali salts are thus seen to be prevented from accumulating through the strata.

Combinations of Fluvial and Aeolian Structures.—The surfaces of arid flood-plains and to a lesser extent those of semiarid climates are dry and barren for a considerable portion of each year, and the detritus becomes reworked by wind action, with the result that in flood plain deposits of desert climates fluvial, pluvial, and aeolian formations are all of wide occurrence and brought into immediate juxtaposition, producing combinations of structures which may be more or less readily recognized in the buried strata. The clayey layers deposited by flood waters crack upon drying into polygonal discs which curl upward on their edges, giving concave mud-cracked surfaces. The fine silt and sand, not possessing coherency when dry, and not being held by vegetation, give rise to intolerable dust storms. The finer silt may cover the adjacent regions with loess and the coarser portions, derived from the stream channels, may be the source of widespread dune sands, such as mantle the deltas of the Indus and the Helmund, burying many ancient cities and subjecting the still exposed ruins to aeolian scour.

The more distinctive structures resulting from the combinations of water and wind action may be classified and described as follows:

First, *mud-cracks filled with aeolian sands.*—Silt and sand will be blown over and fill up the cracks developed by the drying of argillaceous water-laid deposits. Consequently, the sand is filled in under the raised rims of the polygonal discs and becomes continuous with the mantle of sand above. In this way, the concavity upward of the individual plates is preserved and the mud-cracks are not obliterated, even in a silty clay which would slack and crumble immediately upon being rewet by the advancing waters of the following inundation. Experiments by the writer go to show that the upturned edges of the

[1] *Soils*, 1906, chap. xxii.

[2] *Geology of India*, Part I, 1879, p. 413.

clay plates would not usually hold their form while the broad sweep of sand-laden waters should deposit clean sand both under the edges and over the plates. The concavity of the plates thus testifies to aeolian burial and such may be distinguished from mud-cracked flats buried by fluvial action. Since writing a previous article on "Mud Cracks as a Criterion of Continental Sedimentation,"[1] evidence has come to hand from widely separated regions indicating the great geological significance of aeolian-filled mud-cracks in the flood plain deposits of arid climates. A. W. Rogers writing from South Africa makes the following statement:

KHEIS, GRIQUALAND WEST, May 19, 1907.

Today , . . . I happen to be camped on the narrow flood plain of the Orange River which is a fine place for the observation of mud-cracks. The mud flats are exposed for months and even years before being covered again by water. The mud is a gray-brown silt and the cracks become filled with the deep red Kalahari sand from the north. In places the sand advances as fairly high dunes and buries the mud deeply. Generally, however, small thicknesses of the sand are laid down on the mud.[2]

Isaiah Bowman, writing from South America, makes the following statement:

IQUIQUE, CHILI, May 4, 1907.

Along the inner edge of the Desert of Tarapacá, roughly between the towns of Tarapacá and Quillagua, Chili, the piedmont gravels, sands, silts, and muds extend for over a hundred miles, flanking the western Andes and forming a transition belt between these mountains and the interior basins of the coast desert. The silts and muds constitute the outer fringe of the piedmont and are interrupted here and there where sands are blown upon them from the higher portions of the piedmont or from the desert mountains and plains on the seaward side. Practically no rain falls upon the greater part of the desert and the only water it receives is that borne to it by the piedmont streams in the early summer from the rains and melted snows of the high plateau and mountains to the eastward. These temporary streams spread upon the outer edge of the piedmont a wide sheet of mud and silt which then dries and becomes cracked, the curled and warped plates retaining their character until the next wet season, or until covered with wind-blown sand. The wind-driven sand fills the cracks in the muds and is even drifted under the edges of the up-curled plates, filling the spaces completely. Over this combined fluvial and aeolian deposit is spread the next layer

[1] Joseph Barrell, *Journal of Geology*, Vol. XIV (1906), pp. 524–68.

[2] Personal communication to the author.

of mud, which frequently is less extensive than the earlier deposits, thus giving abundant opportunity for the observation of the exact manner of burial of the older sand-covered stratum. The process described above is thought to be of particular interest on account of the generality of its occurrence in this désert.[1]

Ellsworth Huntington contributes the following statement concerning relations observed by him in central Asia:

The floor of the great desert basin of Lop in western China furnishes examples of various associations of mud-cracks with aeolian deposits.

At Yartungaz, 450 miles southwest of Lop-Nor, the floor of the basin consists of a fine-grained saline silt which appears to have been deposited in broad, shallow playas. The surface of the ground is smooth, and there is no sign of buckling, but polygons from three to twelve feet in diameter are plainly visible. The division lines stand out as dark markings dividing the light gray plain into innumerable fairly symmetrical polygons. The prominence of the markings is due to the fact that they are composed of sand which seems to have been blown by the wind into the original cracks in the plain.

A hundred miles farther to the southeast, near Chira, the barrenness of the wind-swept plain of piedmont gravel at the base of the Kwen Lun mountains is slightly relieved by lines of grassy weeds arranged in polygonal patterns like those of Yartungaz. Digging among them, one finds that the plants grow in fine brown sand which fills old cracks in a hard deposit of fine and very saline gravel. The sand is of the same texture as that of the small dunes of the neighborhood.

The most striking case, however, is that of the old bed of the expanded glacial lake of Lop-Nor. For scores of miles a layer of impure rock salt, from one to three inches thick, has split into polygons ranging from five to twelve feet in diameter. The edges have buckled up in exactly the same manner as the edges of ordinary mud-cracks, and frequently stick up two or three feet. The underlying hollows are often partially filled with sand which has been blown in from the distant shores of the lake-bed.[1]

Thus it is seen that this peculiar method of preserval of mud-cracks is widely prevalent at the present time upon the flood-plains of arid regions in various parts of the world. The writer has observed that the same structure has been also widely developed in certain ancient formations.

In the Mauch Chunk shale of Pennsylvania the mud-cracked shale partings between sandstone strata are frequently in the form of tesselated polygonal plates concave upward, the covering layer of

[1] Personal communication to the author.

sand filling the cracks and passing beneath the upraised rims of the plates.[1]

In the Triassic of the Connecticut valley the same structure may be frequently observed, the concave shale plates being in this formation frequently buried in undecomposed feldspathic sand.

Second, *interbedding of fluvial and aeolian sands.*—Gravel and sands which are originally transported by fluvial or pluvial actions upon flood plains in arid climates are later subjected to the action of the wind. Truly fluvial sands and gravels consequently become repeatedly interbedded with aeolian sands, and Huntington states that this is a striking and frequent relation, as seen in the freshly exposed terrace faces on the margins of the desert basins of Asia.

The fluvial and pluvial deposits are characterized by a more heterogeneous and coarser nature and by the absence of the characteristics which mark aeolian sands. It is necessary therefore to summarize some of the distinguishing features of the latter deposits. Dune sands are deposited on the sloping surfaces of the leeward faces of dunes and may reach heights of several hundred feet. At the bottom the inclined layers decrease in dip and pass horizontally to the intervening desert surface. In a region of accumulating sands each passing dune leaves its basal portions to be covered by the march of the following succession of dunes, so that the lower portion of this cross-bedded structure becomes deeply buried and permanently preserved.

As has been recently pointed out by a number of geologists, the characteristic features of such dune sands, separating them from fluvial or littoral deposits, consist consequently in the homogeneous nature, the development of "millet seed" texture, and the presence in striking degree of cross-bedding which may reach great thicknesses. The cross-bedded strata are abruptly truncated above but flatten out and become tangent to the general stratification at the bottom. It is probable that a number of arenaceous formations which have been customarily considered marine are, on the contrary, of such mixed fluvial and aeolian origin. For example, Davis, Huntington, and

[1] For illustrations see Joseph Barrell, "Origin and Significance of the Mauch Chunk Shale," *Bulletin of the Geological Society of America*, Vol. XVIII (1907), Pls. XLIX, L, and Fig. 1, p. 457.

Goldthwait have raised the question if such has not been the mode of origin of the Triassic and Jurassic sedimentary formations of the Colorado plateaus.[1]

Third, *scattered and facetted pebbles.*—In truly aeolian sands the size of the material is rather sharply limited, but in stream channels pebbles or larger fragments may be carried indefinite distances from the fields of erosion. Cloud-bursts and sheet-flood deposition may also sweep large fragments along with the fine, but such action is necessarily more closely limited to the vicinity of the sources of sedimentary supply. In such ways pebbles of various sizes may be clustered or scattered through a finer textured deposit without necessarily implying transportation by either the roots of floating trees, or floating, or glacial ice. Pebbles carried by each of these agencies will be apt to exhibit distinctive characteristics and associations. Those carried by fluvial or pluvial action upon arid flood-plains are the ones to be here considered. The association with various indications of climatic conditions such as those already considered may often suggest the mode of origin. It seems probable, however, that in many instances such pebbles should carry their own evidence through being subjected to wind scour upon the drifting away of the enveloping sand. They would become facetted in consequence, giving rise in the consolidated conglomeratic sandstone to the occasional presence of "dreikanter." Such peculiarly facetted but unstriated pebbles have been collected from a number of formations, dating back even to the pre-Cambrian, but have sometimes been claimed to be of glacial origin. An instance where the hypothesis of aeolian origin appears to offer by far the best explanations has recently been described with illustrations by Lisboa in the case of pebbles which are probably of upper Mesozoic age from the central plateau of Brazil.[2]

Organic characteristics.—Over the more truly desert portions of arid flood plains the life is unimportant at the present time, and in past times has been equally unimportant, if not more so, since the

[1] E. Huntington and J. W. Goldthwait, "The Hurricane Fault in the Toqueville District, Utah," *Bulletin of the Museum of Comparative Zoölogy at Harvard College*, Geological Series, Vol. VI, No. 5, 1904, pp. 210–17.

[2] "The Occurrence of Facetted Pebbles on the Central Plateau of Brazil," *American Journal of Science*, Vol. XXIII, 1907, pp. 9–19.

progress of evolution has been to progressively specialize life forms for such extremely unfavorable habitats. The present relations are briefly as follows:

A sparse vegetation occurs over the drier or more alkaline portions of the plains. Other portions may be covered with dense scrub as seen in the Australian bush. Along the streams tree growth commonly occurs, and hence casts of roots and leaves might be left. In the swamps reed growths are abundant and may become fossilized and associated with white or greenish clay strata.[1] Animal bones embedded in the desert plains stand excellent chances of preserval and observation of the accumulating prairie loess has led Matthew to believe in an aeolian origin for the fine-grained calcareous clays of the White River Tertiary formation covering a considerable area of the Great Plains of the United States,[2] though these tracts are presumed not to have been really arid but rather subarid in climate. The fossil fauna of this deposit as Matthew has shown is such as can be explained by the aeolian hypothesis, but not by one of lacustrine origin.

Ease of recognition in the geological column.—From these characteristic features of the river plains of arid regions it is to be concluded that their fossil representatives should be rather readily recognized. In the marginal region of the delta and for some distance inland beds of salt, gypsum, and marl are interstratified with red shales, in which, however, occasional decolorization may occur. Farther inland the strata will show fewer pure evaporation deposits, but these minerals will still be diffused through the strata. Carbonaceous matter will be practically absent, but well-preserved animal remains may be abundant. Dune sands, characterized by cross-bedding and a high degree of rounding, giving "millet seed" sand beds such as those which Phillips has described from the English Triassic,[3] will be associated with true river deposits, sometimes mud-cracked, and the whole will be characterized by a relative absence of rock decay in the process of sedimentation.

[1] Huntington, "The Basin of Eastern Persia and Sistan," *Carnegie Institution*, 1905, pp. 279–87.

[2] W. D. Matthew, "Is the White River Tertiary an Aeolian Formation?" *The American Naturalist*, Vol. XXXIII, 1899, pp. 403–8.

[3] J. A. Phillips, "On the Constitution and History of Grits and Sandstones," *Quarterly Journal of the Geological Society*, Vol. XXXVII, 1881, p. 26.

THE CLIMATIC SIGNIFICANCE OF COLOR

One of the most obvious features of the sedimentary rocks is their color, due partly to climatic, partly to various other, conditions of origin. Among the latter Walther calls attention to the fact that—

> The colors of continental deposits are different according as they are formed above or below a water surface. The deposits in the courses of streams or in interior seas have usually either greenish or bluish colors which also characterize the marine deposits of the continental shelves. The typical continental deposits, formed upon the dry land, are characterized by bright clean colors. The carmine or vermilion tropical laterite, the red-colored sand dunes of the Coromandel lowland and the inner Arabian desert, the yellow or brown loam and loess deposits of the steppes, the white or yellow dunes of the coast lands or the Sahara are convincing examples.[1]

The influence of climate as distinct from other conditions of origin is rendered evident on contrasting the brilliant reds of the moist tropical or subtropical regions with the yellow or dark soils of colder temperate climates or the prevailing ashen gray of deserts. The significance of color in the older rocks cannot, however, be directly inferred from the study of modern deposits since the changes which transform a soft sediment into a solid rock may also conceivably alter the color.

For the purposes of the present discussion, the colors of shales and sandstones may be grouped under three heads: first, red; second, light and variegated; third, gray to black. Each of these color groups is of importance and includes appreciable portions of the sedimentary rocks. On account of the diversity of views, however, respecting the significance of red and its climatic bearings, it will be necessary greatly to enlarge the discussion upon that topic.

The origin of red formations.—Red shading into brown is one of the most frequent colors of ancient continental shales and sandstones and may also occur among those of marine origin. That there is no unanimity in regard to its significance among geologists may, however, be gathered from an examination of the literature. Russell has given a full review of these views.[2] Certain authors have supposed

[1] *Einleitung in die Geologie*, translated from *Lithogenesis der Gegenwart*, 1893–94, p. 725.

[2] "Subaerial Decay of Rocks and Origin of the Red Color of Certain Formations," *Bulletin 52*, U. S. Geological Survey, 1899, pp. 47–56.

that the red is due to igneous agencies, oxidizing iron pyrites, or to volcanic dust or the heat of igneous intrusions. All such hypotheses fail, owing to the widespread occurrence of red rocks, their uniform color, and the absence of metamorphism. Another group of hypotheses ascribes the oxidation to weathering at the time of origin of the sediments and this is undoubtedly correct, the iron peroxide being a component part of the accumulating sediments. Nearly all writers, however, assume that the oxide which is now more or less completely dehydrated and consequently red was in this dehydrated state at the time the sediments were deposited. This assumption runs through the work of Russell and is the basis of many such statements as that of Darton that "red shales and sandstones, such as make up the red-beds, usually result directly from the revival of erosion on a land surface long exposed to rock decay and oxidation and hence covered by a deep residual soil. . . . . There is such uniformity of the deep-red tint that this is undoubtedly the original color."[1] Russell considers that the incrustation of the sandstone grains of the Newark formation by ferric oxide, resembling that surrounding the grains of quartz in the residual soil of the southern states, indicates that the grains were transported without sufficient wear to remove the original incrustation. From the distribution of present red earths, he further concludes that their formation requires the presence of heat and moisture. All such special modes of origin, however, are difficult of acceptance in view of the great predominance of red, or red-brown in ancient ferruginous formations and the comparative absence of yellow tones such as dominate modern alluvium.

In view of such a conflict of opinions and the special nature of the hypotheses used to explain the general nature of the phenomenon, the need of discussion is seen. Certain essential facts which have bearings on the conclusions may be stated as follows: As indicating the influence of a moist climate, Russell notes the brilliant reds and yellows of the soils of the South Atlantic states as compared with the ashen tints of the Mojave desert,[2] and he elsewhere speaks of the creamy-white color of the playa-lake deposits of Nevada and Arizona,

[1] "Geology of the Bighorn Mountains," *Professional Paper No. 51*, U. S. Geological Survey, 1906, pp. 105–7.

[2] I. C. Russell, *op. cit.*, p. 27.

beds exposed during the summer months to temperatures of from 110° to 120° Fahr. in the shade.[1] As indicating the influence of heat may be mentioned the uniform restriction of red soils, neglecting those derived directly from red formations, to the warm temperate and especially the torrid zone. That the contrast is not due to the younger age or glacial origin of the soils of the cold temperate zones is found upon examination of driftless areas in such regions. As indicating the influence of prolonged exposure to the air, Crosby notes that it is the older soils and especially the surface portions in the warm regions which show red to a striking degree.[2]

Where reds in surficial formations are noted in arid regions they are frequently the accompaniments of aeolian action. Dune sands may be white, yellow, or red. Red deserts have been noted in both Africa and Asia and Phillips has shown that the red sands of the Arabian desert owe their color to a coating of ferric oxide deposited after the grains of sand had become round. The source of the iron oxide, which comprised about 1–500 of the total weight, he was unable to determine.[3] All these facts emphasize the influence of lapse of time and the presence of moderate heat, such as that of the torrid regions, as causes sufficient partially to effect the dehydration of ferric oxide, even without the agency of pressure; thereby transforming the yellow and light-brown colors into the brilliant reds which characterize the tropical regions of rainy climate.

In view of these facts, one of the chief true causes of the red color of the older ferruginous formations seems to have been reached by Crosby, whose statements are as follows:

> The dehydration of the ferric oxide is not wholly dependent upon heat or pressure or any obvious extraneous agency, but it is in a large degree, apparently, a spontaneous process. Of this we have abundant evidence in nature and in the laboratory. When the iron, which exists in the various silicate minerals chiefly in the ferrous state, is liberated and peroxidized during the decay of these species, it combines naturally with a very large and indefinite proportion of water, forming the yellow hydrate, which is seen as a flocculent or a gelatinous colloid in the waters of springs, bogs, and marshes, and when the hydrate is obtained as

[1] *Op. cit.*, p. 42.

[2] On the contrast in color of the soils of high and low latitudes, *American Geologist*, Vol. VIII, 1891, p. 77.

[3] "The Red Sands of the Arabian Desert," *Quarterly Journal of the Geological Society*, Vol. XXXVIII, 1882, pp. 110–13.

a precipitate in the laboratory. But this colloid mass, even if immersed in water and entirely undisturbed, gradually and spontaneously gives off a large part of the water which the ferric oxide has so greedily absorbed when in the nascent state; and it appears thus, as it slowly solidifies and hardens, to pass in succession through the forms of the various native yellow hydrates—limnite, *xanthosiderite*, and limonite, to göthite. That this progressive change continues is evident from the fact that these yellow hydrates are gradually replaced in the older formations by the red hydrate (turgite) and by ferric anhydride (hematite). When occurring as original or contemporaneous, and not as secondary, deposits, the yellow ores of iron are found, as a rule, only in the later rocks; while the red ores are generally restricted to the earlier rocks. This genetic relation of the yellow and red ores is one of the most familiar and generally accepted facts in geology. However recent the origin of the red ore (turgite or hematite) may appear to be in any case, we naturally infer that it was first yellow, and that it has passed slowly or rapidly, as the case may be, but gradually, through the series of yellow hydrates. . . . .

If it be conceded that the dehydration is virtually, if not absolutely, spontaneous, and there is no apparent alternative, it follows that the color of a deposit, so far as it is due to ferric oxide, is, other things being equal, a function of its geological age. In other words, the color naturally tends with the lapse of time to change from yellow to red; and, although this tendency exists independently of the temperature, it is undoubtedly greatly favored by a warm climate. Applying this principle to the sedimentary soil of the South, we find that the superficial portion is red, not alone because it is exposed to a higher temperature than the subjacent yellow clay, but also because it is the oldest part. On the other hand, the limited occurrences of post-glacial sedimentary detritus in the North are, in the absence of the favoring climatic influence, still too young to exhibit the change of color even superficially.[1]

Judging from the later expressions of opinion, this article does not seem to have received the attention which it deserves.

Spontaneous dehydration assisted by heat and favored by time does not appear, however, to be the sole cause of the great contrast in color between the consolidated and the surficial ferruginous sediments, a still more potent cause existing in the dehydration effected by the great increase in pressure and moderate rise in temperature which takes place upon the burial of the material to some thousands of feet beneath later accumulations. The efficiency of pressure in this connection is exhibited in the formation of shales, where about one-half of the combined water is eliminated at temperatures which must be frequently far below the boiling-point, since with the normal gradient

[1] *Op. cit.*, pp. 80, 81.

a temperature of 110° C. is attained only at a depth of about 11,000 feet (3,300 meters). The ferric oxide, holding its water with much less tenacity than the silicate of alumina, seems to respond most readily to the influence of pressure, giving rise to minerals of notably less volume and greater density, apart from the water which is eliminated in the process.

Still a third factor in the development of a red color in ferruginous rocks is found in the physical state of the oxide, as may be seen upon contrasting the brilliant color of earthy hematite with the deep colors of the same mineral in its crystalline form. The red color depends therefore not only upon the presence of anhydrous or partially anhydrous ferric oxide, but also upon a fine state of division and diffusion. Dawson speaks of the very fine state of division of the red coloring matter in the lower Carboniferous of Nova Scotia—

having indeed the aspect of a chemical precipitate rather than of a substance triturated mechanically. In addition to the oxide of iron distributed through the beds, there is, in the fissures traversing them, a considerable quantity of the same substance in the state of brown hematite and red ochre, as if the coloring matter had been superabundant or had been in part removed and accumulated in these veins.[1]

Hilgard states further that the general red aspect of tropical soils is by no means always accompanied by markedly high percentages of ferric oxide, but the latter is very finely diffused so as to be very effective in coloration. The soils of the arid regions on the other hand are not deficient in ferric oxide.[2] The present writer has also noted that pebbles of feldspar showing glistening cleavage embedded in the red Triassic arkoses of the eastern United States are stained red throughout with ferric oxide while those of quartzite are stained to variable depths and those of vein quartz only along the fractures. The completeness of the staining, its development about the stream-worn surfaces of pebbles, and its presence in all materials, depending only upon their porosity, are indications that this was done after incorporation in the sediments and through a considerable period of time. The above facts seem to show that ferric oxide in rocks is rather readily

[1] J. W. Dawson, "On the Coloring Matter of Red Sandstones and of Greyish and White Beds Associated with Them," *Quarterly Journal of the Geological Society*, Vol. V, 1848, pp. 25, 26.

[2] Hilgard, *Soils*, 1906, pp. 392, 400.

diffusable, permeating the entire rock mass and thereby becoming more effective as a coloring substance. In view of this ready diffusability and ease of dehydration, such a special hypothesis as that of Russell—that the crusts of ferric oxide had been retained by sand grains during their transportation from a residual soil—seems unnecessary and as a general explanation does not apply.

To sum up, it is seen that the cause of the red color in ferruginous rocks as contrasted with the predominant yellows of modern alluvium is to be found in three co-operating causes: First, spontaneous dehydration operates to some extent at the surface in the warmer regions. Second, dehydration under great pressure and moderate temperatures is nearly universal in sediments which become buried and consolidated. Third, diffusion operates under conditions of warmth and moisture, whether these be found at the surface, as in warm and humid regions, or beneath the surface, as may occur in any portion of the earth. By these three means light-colored, yellow or brown muds and sands may become red shales and sandstones. Only in the presence of considerable heat, as on the walls of dikes, or in the presence of some highly dissolving fluid does the tendency toward crystallization or new combination reverse the coloring effects of capillary diffusion.

Red in shales or sandstones is therefore normally assumed, like the hardness, upon the consolidation into a shale or sandstone of any sediment possessing an appreciable amount of ferric hydrate and is no more necessarily original than is the red of a burned brick.

The reliability of these conclusions may be tested by observing the stratigraphic relations of ancient deposits. As a typical example may be cited the Permian red-beds developed east of the Rocky Mountains, which contain conspicuous strata of gypsum and are impregnated with salt, giving thus undoubted evidence of deposition under an arid climate. The same association of salt and gypsum with red shales and sandstones might be cited from Nova Scotia and a dozen other localities.

This is in striking contrast to the usual present development of salt and gypsum in association with gray or yellow sediments. For example, the marginal bottom of the Dead Sea when exposed by unusual dessication shows a surface of bluish-gray clay or marl full of crystals of common salt and gypsum, and light-grays are char-

acteristic also of the salty flats in the Great Basin of the United States. Furthermore, the Red Sea, surrounded by intensely arid lands, shows dominant light yellow as the color of the bottom muds, varying in certain soundings to tones of grayish or brownish yellow.[1] Contrary to what might be expected from the name, the Red Sea contains no red sediment and the origin of the name is in doubt.[2]

From these statements it is seen that, while red in present soils is particularly characteristic of the residual soils of warm moist climates, in ancient deposits it is a usual accompaniment of arid conditions.

Furthermore, that hot climates were not necessary for the origin of certain ancient red shales and sandstones is suggested, but far from proved, by the occurrence of such rocks within the Arctic Circle, Nathorst having found the Old Red Sandstone in Spitzbergen, lat. 79–80° N.[3] On Bear Island, also, somewhat farther to the south, in lat. 74° 30′ N., and again in northern Norway, red strata of this age occur.[4] Turning to the antipodes, it is to be noted that Wilkes in 1840 landed on an ice island off the Antarctic continent in lat. 65° 60′, long. 106°19′ E. He found imbedded in it, in places, bowlders, stones, gravel sand, and mud or clay. The larger specimens were of red sandstone and basalt.[5] The "Challenger" expedition in 1874 in the vicinity of the Antarctic ice in lat. 65° 42′, long. 79° 49′ E., dredged up specimens of igneous and metamorphic rocks and red sandstone.[6]

That a special origin, such as by "the revival of erosion on a land surface long exposed to rock decay and oxidation and hence covered by a deep residual soil," is not necessary is indicated by the very great thickness and uniform color of certain red formations; by the

[1] Joseph Luksch, "Vorläufiger Bericht über die physikalisch-oceanographischen Untersuchungen im Rothen Meere," *Wiener Akademie Sitzungsberichte, Mathematisch-Naturwissenschaftlichen Classe*, Abtheilung I, Band CVII (1898), pp. 636, 637.

[2] Major J. S. King, "The Red Sea: Why so Called," *Journal of the Royal Asiatic Society* (1898), pp. 617, 618.

[3] E. Suess, *Das Antlitz der Erde*, Eng. trans., Vol. II, pp. 68, 69.

[4] A. Geikie, *Text Book of Geology*, 4th ed., 1903, pp. 1012.

[5] *Narrative of the United States Exploring Expedition During the Years 1838–1842*, Vol. II, p. 325.

[6] John Murray, "Deep Sea Deposits," "*Challenger*" *Reports* (1891), pp. 80, 81.

inclusion of conglomerates whose component pebbles frequently consist of fresh blocks of granite, pegmatite, and other rocks subject to decay, testifying to a partial dominance of disintegration over decomposition; by such an example as the Mauch Chunk red shales and sandstones, 3,000 feet in maximum thickness, following immediately upon the gray Pocono sandstone and its gradual transition above into Pottsville conglomerate, red shales alternating with conglomerate horizons.

That conditions of deposition permitting oxidation had much to do with the development of red in the consolidated sediment is indicated by the usual poverty in fossils, especially in those of marine origin; by the repeated intercalation in the Basin of Sistan of pink to brown silts, regarded by Huntington as having been deposited subaerially, with green clays, considered with good evidence as typically lacustrine.[1] As a further illustration, the Wamsutta red-beds of the Carboniferous of the Narragansett basin are regarded by Woodworth as represented south of Providence by the lower strata of the Kingstown coal-bearing series. In the vicinity of Pawtucket the coal-measures underlie the Wamsutta, though somewhat farther north the latter are only separated from the granite by the basal arkose beds of the Pondville group.[2] Woodworth states that the coloring of the Wamsutta red-beds appears to have taken place before transportation. This view, however, leads to difficulties which he states on the same page. All difficulties, seem, however, to be avoided if it be considered that the red is the result of dehydration during consolidation and that these beds retained their iron because they were deposited in an upper and better-drained portion of the basin under a climate which permitted for a time their seasonal drying.

Turning to the climatic significance of red, it would therefore appear both from theoretical considerations and geological observations that the chief condition for the formation of red shales and sandstones is merely the alternation of seasons of warmth and dryness with seasons of flood, by means of which hydration, but especially

[1] *The Basin of Eastern Persia and Sistan*, "Carnegie Institution Publications," No. 26, 1905, p. 287.

[2] "Geology of the Narragansett Basin," *Monograph XXXIII*, U. S. Geological Survey, 1899, pp. 134, 141.

oxidation of the ferruginous material in the flood-plain deposits is accomplished. This supplements the decomposition at the source and that which takes place in the long transportation and great wear to which the larger rivers subject the detritus rolled along their beds. The annual wetting, drying, and oxidation not only decompose the original iron minerals but completely remove all traces of carbon. If this conclusion be correct, red shales or sandstones, as distinct from red mud and sand, may originate under intermittently rainy, subarid, or arid climates without any close relation to temperature and typically as fluvial and pluvial deposits upon the land, though to a limited extent as fluviatile sediments coming to rest upon the bottom of the shallow sea. The origin of such sediment is most favored by climates which are hot and alternately wet and dry as opposed to climates which are either constantly cool or constantly wet or constantly dry.

The origin of light and variegated colors.—White or light gray in rocks indicates an absence of iron, an absence which may be due to entirely mechanical causes, as in white clean sandstones of either fluvial, pluvial, marine, or aeolian origin; or to chemical causes, as in gray or black clays.

Aeolian deposits whether coarse or fine, as dune sand or loess, are typically light in color, varying from nearly white to pale yellow or pink. The lightness in color appears to be due in dune sand to the mechanical segregation of the grains, but in loess partly to the lack of decomposition, partly to the lack of diffusion of the coloring substance. The preceding discussion upon the significance of red would suggest that loess deposits older than the Pleistocene should be dominantly colored from white to light pink rather than the more customary pale buff of the recent deposits. Upon weathering, however, such a buff color would tend to be to some extent restored on account of the porous nature and the new decomposition which is possible in the case of loess.

Where lightness in color is due to chemical causes it is to be noted that the first result of the action of fermenting organic matter upon ferruginous clays is a change of color from rusty to bluish or greenish by the reduction of ferric to ferroso-ferric hydrate. Afterward, if the action be continued, the solution of ferrous carbonate may be formed, and the greenish or bluish color may disappear. The impor-

tance of this reaction lies in the fact that the blue or green tint, wherever it occurs, indicates a lack of aeration, usually by the stagnation of water, in consequence of imperfect drainage.[1]

It is seen in conclusion that where the light color is due to mechanical causes the mode of origin of the formation and the climatic conditions must be determined on other grounds than color. Further, where limited development of white, gray, green, or blue occurs, owing to chemical action upon the iron, the conditions represent a variable balance between the action of iron and carbon determined by local topographic rather than climatic conditions. Where such colors are rather abundant, however, over broad areas of non-marine formations a mean, rather than an extreme, climate is indicated.

The origin of gray to black formations.—The conclusions on this topic are rather obvious from the preceding discussion on the "effects of constantly rainy climates." They need, therefore, only be summarized at this point for completness.

Where a whole formation, representing an ancient floodplain or delta, shows in its unweathered portions an absence throughout of the colors due to iron oxide, and a variable presence of carbon, giving grays to black, the inference is that the formation accumulated under a continuously rainy climate or one which in the drier season was sufficiently cool or cold to prevent noteworthy evaporation; such climates as exist in Ireland, Iceland, or western Alaska; to a minor extent on windward slopes in the trade-wind zones and also to a minor extent in a few tropical belts which never quite escape from the shifting zones of tropical rains.

CONCLUSIONS ON CLIMATIC INFLUENCES IN REGIONS OF DEPOSITION

It was seen in the discussion on the relations of climate to regions of erosion that climate was one of the controlling factors in determining the quantity, but more especially the physical and chemical nature, of the sediment supplied to the rivers. But some large river systems have their sources in climatic zones distinct from that of their lower courses. Furthermore, the comminution and decay involved in transportation and the varied contributions of tributaries obscure

[1] Hilgard, *Soils*, 1906, p. 45.

to an extent, depending upon the size of these factors, the climatic indications given by erosion. In proportion as such occur, however, the climatic influences in the region of deposition grow more pronounced, until finally over the larger deltas, where the fine-grained waste is deposited on nearly horizontal surfaces, the climatic effects become a dominant influence in the nature of sedimentation.

From the extremes of cool and rainy climates on the one hand to hot and arid on the other a gradation in character of deposits may be observed corresponding to that gradation which exists in climatic cause. For the sake of discussion, however, artificial division lines must be drawn separating the climates into several categories, as has been done. In consequence, except in clearly marked instances there may be some doubt as to the exact climatic division to which a certain deposit belongs. To reach the greatest certainty every line of evidence must be followed to its end and given appropriate weight in governing the conclusion. Only by the convergence of many probabilities may reasonable certainty be attained.

The most obvious chemical features of subaerial river deposits which depend upon the climatic gamut consist in the antithetical relations of carbon and ferric oxide. Supplemental to these two chief indicators stand the other more or less soluble substances, magnesium and calcium carbonates, hydrous calcium sulphate, sodium and potassium chlorides; wholly absent from river deposits of the one climatic extreme, appearing in successive order in deposits made under climates representing gradations toward and to the other. Supplemental to these primary chemical distinctions are the textural, structural, and organic evidences.

Varying powers of erosion and transportation giving rise to varying quality and quantity of sediment are seen to be the most delicate stratigraphic indicators of *climatic fluctuations*. On the other hand the chemical and organic conditions accompanying the deposition of the sediment upon the delta plain are the more secure indicators of the *stable and average climatic conditions* under which the formation as a whole was made.

(*To be concluded*)